CHANDRA Detection of the AM CVn binary ES Cet (KUV 01584-0939)

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ABSTRACT

We report on *Chandra* ACIS observations of the ultracompact AM CVn binary ES Cet. This object has a 10.3 minute binary period and is the most compact of the confirmed AM CVn systems. We have, for the first time, unambiguously detected the X-ray counterpart to ES Cet. In a 20 ksec ACIS-S image a point-like X-ray source is found within 1" of the catalogued optical position. The mean countrate in ACIS-S is 0.013 s^{-1}, and there is no strong evidence for variability. We folded the X-ray data using the optical ephemeris of Warner & Woudt, but did not detect any significant modulation. If an $\approx 100\%$ modulation similar to those seen in the ultracompact candidates V407 Vul and RX J0806.3+1527 were present then we would have detected it. The upper limit (3σ) to any modulation at the putative orbital period is $\approx 15\%$ (rms). We extract the first X-ray spectrum from ES Cet, and find that it is not well described by simple continuum models. We find suggestive evidence for discrete spectral components at ≈ 470 and 890 eV, that can be modelled as gaussian emission lines. In comparison with recent X-ray detections of nitrogen and neon in another AM CVn system (GP Com), it appears possible that these features may represent emission lines from these same elements; however, deeper spectroscopy will be required to confirm this. Our best spectral model includes a black body continuum with $kT = 0.8$ keV along with the gaussian lines. The unabsorbed 0.2 - 5 keV X-ray flux was $\approx 7 \times 10^{-14}$ ergs cm^{-2} s^{-1}. The observed luminosity in the hard component is a small fraction of the total expected accretion luminosity, most of which should be radiated below 0.1 keV at the expected mass accretion rate for this orbital period. We discuss the implications of our results for the nature of ES Cet.

Subject headings: Binaries: close - Stars: individual (KUV 01584-0939, ES Cet, Cet3) - Stars: white dwarfs – X-rays: binaries – Gravitational Waves

1. Introduction

The AM CVn stars are a class of ultracompact, semidetached binaries which are transferring helium from a degenerate (or semi-degenerate) dwarf onto a companion white dwarf (see Warner 1995). There are presently ten confirmed systems of this type (Woudt & Warner 2003), and an eleventh has recently been proposed (SDSS J1240-01; Roelofs et al. 2004) based on optical spectroscopy. ES Cet (also known as KUV 01584-0939, and Cet3) was discovered in the Kosi survey for UV-excess objects (Kondo, Noguchi & Maehara 1983), and it is also listed in the CV catolog of Downes, Webbink, & Shara (1997). Its optical spectrum was studied by Wegner, McMahan & Boley (1987) and shows strong He II emission lines. A strong blue continuum, likely due to accretion, is also present and provides additional evidence that the system is a compact binary. Recently, Warner & Woudt (2002) strengthened this conclusion with the report of a 10.3 minute modulation of its V band flux. The modulation is very likely the orbital period or a "superhump" period of an AM CVn binary. The superhump periods in AM CVn's are thought to be caused by disk warping and precession, and are typically found just longward of the orbital periods (see Patterson et al. 2002; Warner 1995). The 10.3 minute orbital period makes ES Cet the most compact of the *bona fide* AM CVn stars. Two additional AM CVn candidates with shorter periods have recently been proposed; V407 Vul (Cropper et al. 1998; Ramsay et al. 2000; Marsh & Steeghs 2002; Wu et al. 2002; Strohmayer 2002; Strohmayer 2004a) and RX J0806.4+1527 (Israel et al. 2002; Ramsay et al. 2002; Hakala et al. 2003; Strohmayer 2003), however, it is still possible that the observed periods in these systems are not the orbital periods of ultracompact systems (see Cropper et al. 2003; Warner 2003; Norton, Haswell & Wynn 2004; Strohmayer 2004a).

If ES Cet is indeed an ultracompact binary, then gravitational radiation can drive mass transfer at a rate as high as $1 \times 10^{-8} M_{\odot}$ yr^{-1}, and the object should be a bright soft X-ray source. Several AM CVn systems have been detected in the X-ray band, including AM CVn, CR Boo and GP Com (van Teeseling & Verbunt 1994; Ulla 1995; Eracleous, Halpern & Patterson; and Strohmayer 2004b). Indeed, recent XMM/Newton observations of GP Com have provided, for the first time, both high signal to noise spectra as well as detections of X-ray emission lines from an AM CVn system (Strohmayer 2004b). These results indicate that X-ray spectral studies can provide detailed information about the accretion process as well as the composition of the accreted matter in such systems. It is therefore important to expand the X-ray sample and identify additional targets suitable for more comprehensive follow-up. Moreover, as the most compact of the confirmed AM CVn stars, ES Cet should be a strong gravitational radiation source, and changes in the orbital period should be measureable (see Woudt & Warner 2003; Strohmayer 2004a).

The ROSAT all sky survey (RASS) faint source catalog shows a 0.0166 counts s^{-1} source, 1RXS J020052.9-092435, within $\approx 10''$ of ES Cet, however, the source is too faint to provide any useful X-ray colors, and ROSAT's positional accuracy is not sufficient to unambiguously confirm it as the X-ray counterpart to ES Cet (Voges et al 2000). Here we present new *Chandra* observations which have unambiguously identified the X-ray counterpart to ES Cet, further solidifying its accreting, ultracompact credentials. In §2 we give a brief overview of our *Chandra* observations and the imaging analysis. We discuss our spectral and timing analyses in §3. We close in §4 with a discussion of the implications of our findings for the nature of ES Cet.

2. Data Extraction and Analysis

Chandra observed the region around ES Cet for $\approx$ 20 ksec on October 2, 2003 (TT). Imaging was performed with ACIS-S using TIMED-FAINT mode and the aimpoint was on the ACIS-S3 backside illuminated chip. We used the FTOOLS version 5.3 to extract an image centered on the optical position of ES Cet. We then employed the CIAO tool *wavdetect* to search the image for point sources. Figure 1 shows the central portion of the ACIS-S3 image. Seven new X-ray sources are detected in this field with $> 4\sigma$ significance (the sources are marked with 3" radius circles), including a source at a location consistent with the optical position of ES Cet ($\alpha = 02:00:52.23$,$\delta = -09:24:31.68$; J2000). Table 1 summarizes some of the basic properties of all these sources. This object, which we denote CXO 020052.2-092431.6, is additionally marked with the pair of orthogonal lines in Figure 1. Its derived position is within 1" of the optical position of ES Cet. Based on the positional coincidence and the gross X-ray properties described below we conclude that CXO 020052.2-092431.7 is the X-ray counterpart to ES Cet. The detection of the source in X-rays provides additional confirmation that it is indeed an accreting, ultracompact binary.

3. Timing and Spectral Properties

To probe the X-ray timing and spectral properties of ES Cet we first used the CIAO tool *axbary* to correct the photon arrival times to the solar system barycenter. For this we used the source coordinates obtained from our imaging analysis above. We then extracted photons in an $\approx 1.5''$ region centered on the source. This resulted in a total of 249 photons for our analyses. Figure 2 shows a lightcurve, using all source photons binned at 1,000 seconds. The mean countrate is 1.25×10^{-2} s^{-1}. There is no strong evidence for variability in the lightcurve.

To search for a modulation at the observed optical (presumably orbital) period we folded the data using the ephemeris of Woudt & Warner (2003), but we did not detect any significant modulation. We also computed a Z_n^2 power spectrum (see Buccheri et al. 1983; Strohmayer 2002), which allows a search for periodic signals with arbitrary harmonic content, n. We used $n = 3$ for consistency with the pulse profiles from V407 Vul and RX J0806 which have this number of significant harmonics. Consistent with the folding analysis, no signal is detected in the Z_3^2 spectrum. We can place an upper limit on the signal power using the Z_3^2 power level found in the immediate vicinity of the optical frequency. Expressed as an amplitude, this gives a (3σ) upper limit of 15% (rms). This limit is consistent with the value $a = 1/2(I_{max} - I_{min})/(I_{max} + I_{min})$, where I_{max} and I_{min} are the maximum and minimum values of the folded profile, respectively. The quantity a is a convenient, frequently used measure of the amplitude of a pulsed signal.

Interestingly, if the source had an X-ray modulation profile similar to those seen from V407 Vul and RX J0806.4+1527, then we would have easily been able to detect it. Our ability to detect a signal of a given strength in these data can be quantified using the so called signal sensitivity, which is the pulsed amplitude that, if present, would be detected with at least a given confidence level. For these data we have a 3σ sensitivity to a pulsed X-ray flux at the known orbital period of $\approx 28\%$ (rms).

We extracted source and background spectral files, used the CIAO tools to generate response matrices and modelled the spectrum within XSPEC. The low energy response of ACIS is effectively reduced and modified by a contaminant (Marshall et al. 2003). To account for this we used an ancillary response file (ARF) corrected with the ACISABS tool. We began by fitting several simple continuum models, including, power-law, black body, and thermal bremsstrahlung spectra. Using these continuum models we found there is essentially no sensitivity to a neutral hydrogen absorbing column, so we fixed $n_H = 0.02 \times 10^{22}$, which is the value deduced from the "n_H" tool available at the HEASARC webpage (Dickey & Lockman 1990). We found that the best fitting thermal bremsstrahlung temperature was > 100 keV. Over the bandpass of interest this spectral form looks essentially like a power-law. Since the two models have essentially the same goodness of fit, for the sake of brevity we do not give further details of the fits for the bremsstrahlung model.

Given the relatively modest number of counts it is perhaps surprising that none of these continuum models alone does a very good job of fitting the spectrum. See Table 2 for a summary of the spectral fits. For each of these models the additional contribution to χ^2 appears to be associated with localized emission at about 0.9 and 0.5 keV, respectively. These excesses can be adequately modelled with gaussian emission line profiles. Including these two additional components we find that the best overall model is the black body continuum

(plus the gaussian lines). This fit has a minimum $\chi^2 = 13.5$ with 23 degrees of freedom. For comparison, the power-law model including the two emission lines achieves a minimum $\chi^2 = 23.7$, which is formally acceptable, but not as good as the fit using the black body continuum with lines. We show the data and the best fit with this model in Figure 3. Using our best spectral model, the unabsorbed X-ray flux in the 0.2 - 5 keV band is 7.1×10^{-14} ergs cm^{-2} s^{-1}. An absorbing column of 2×10^{20} cm^{-2} reduces this number by 3%.

The significance of the line components can be estimated by evaluating the significance of the change in χ^2 using the F-test. However, a difficulty with this procedure is that the continuum is not known *a priori*. Using the power-law continuum and fitting each line separately we find $\Delta\chi^2 = 5.4$ and 7.7 for the 470 and 890 eV features, respectively, while including both lines simultaneously gives $\Delta\chi^2 = 15.1$. These numbers correspond to F-test probabilities of 0.148, 0.055, and 0.0135, respectively. Using the blackbody continuum results in $\Delta\chi^2$ values of 20.8, 13.1, and 35.7 for the 470 eV, 890 eV and simultaneous fits. This yields F-test probabilities of 0.0012, 0.021, and 5×10^{-6}, respectively. Because we do not know *a priori* the form of the continuum, and since the lines are not compellingly significant against the power-law continuum, we regard the present evidence for the line features as suggestive, requiring confirmation with higher signal to noise measurements.

We note, however, that recent high resolution X-ray spectral measurements of the AM CVn system GP Com (Strohmayer 2004b) have revealed strong nitrogen emission lines at $24.78\AA = 500.4$ eV (N VII Lyα), and $\approx 29\AA = 427.6$ eV (N VI). When observed with the lower resolution of a CCD, such nitrogen emission could produce a feature with a centroid energy consistent with the ≈ 500 eV feature tentatively identified in ES Cet. Moreover, strong lines of hydrogen- and helium-like neon were also detected in GP Com. A possible origin for the ≈ 900 eV feature suggested in the spectrum of ES Cet could be emission from helium-like neon at $\approx 13.5\AA = 918.5$ eV, however, this would require very little neon in the hydrogen-like ionization state (Ne X Lyα at $12.134\AA = 1,021.9$ eV), since there is no evidence for an emission line component in ES Cet at ≈ 1 keV.

4. Discussion and Implications

The gravitational radiation torque on an ultracompact binary is a strongly increasing function of the orbital frequency. For an ≈ 10 minute system like ES Cet, the mass accretion rate should approach $1 \times 10^{-8}\ M_\odot$ yr^{-1}. Assuming that matter falls from the inner Lagrange point, and that half the gravitational potential energy is dissipated in the accretion disk, the

X-ray luminosity, L_x, can be expressed as (see, for example, Nelemans et al. 2004),

$$L_x = \frac{1}{2}\frac{GM_1\dot{m}}{R}\left(1 - \frac{R}{R_{L_1}}\right) , \tag{1}$$

where M_1, R, R_{L_1}, and $\dot{m}$ are the primary mass, primary radius, the distance from the inner Lagrange point to the center of the accretor, and the mass accretion rate, respectively. With $\dot{m} = 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ this expression predicts a luminosity of $\approx 3.4 \times 10^{34}$ ergs s^{-1}.

The X-ray flux from accreting, non-magnetic white dwarfs is likely produced in a boundary layer whose properties are a strong function of the mass accretion rate. At the high rates expected for ES Cet the boundary layer should be optically thick, radiating with an effective temperature in the range $3 - 5 \times 10^5$ K (see for example, Pringle & Savonije 1979; Narayan & Popham 1993). The spectrum we see with *Chandra* is clearly much harder than a simple black body at $\approx 5 \times 10^5$ K (0.043 keV). The distance to ES Cet is not well constrained, however, even at a distance of 1 kpc the observed 0.2 - 5 keV flux corresponds to a luminosity of 8.3×10^{30} ergs s^{-1}, which is much less than that expected for $\dot{m} = 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$. Clearly the hard X-ray flux observed with *Chandra* represents a small fraction of the total accretion luminosity.

If the accretion rate is indeed as high as $10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$, then the boundary layer is expected to be optically thick, and the bulk of the accretion luminosity should be emitted below 100 eV. For example, a thermal spectrum with $T = 4 \times 10^5$ K would peak at ≈ 100 eV, below the nominal *Chandra* band. Moreover, even a modest interstellar column would strongly absorb such a soft component. Although the uncertainty in n_H makes it difficult to be precise, we can put some constraints on the strength of such a component. Assuming a 40 eV blackbody temperature, and taking $n_H = 0.02 \times 10^{22}$ cm^{-2}, we find that such a component could have an intrinsic flux as large as $2 - 4 \times 10^{-13}$ ergs cm^{-2} s^{-1} before a soft excess becomes evident in the lowest energy channel of the *Chandra* spectrum. If the temperature were as low as 30 eV then it would not be too difficult to hide an even larger flux of $\approx 1 - 2 \times 10^{-12}$ ergs cm^{-2} s^{-1}. We note that *Chandra's* low energy sensitivity is further compromised by the ACIS contaminant. Better sensitivity at and below 100 eV will be required to adequately address the issue of the bolometric accretion luminosity of ES Cet. A distance measurement would also be extremely useful in constraining the energetics of the system.

The detection of ES Cet as an X-ray source further solidifies its ultracompact credentials. Comparisons with the two ultracompact candidates; V407 Vul and RX J0806.4+1527 could therefore lead to insights as to the true nature of these systems. Although ES Cet has a photometric period similar to both of the ultracompact candidates, there would appear to be important differences between the systems. ES Cet has a much harder spectrum than either

V407 Vul or J0806, which both show essentially no emission above 1 keV. Thus, if accretion powers the emission in all three sources, there must be something different about the nature of the accretion. The lack of strong variability in ES Cet suggests the X-ray emission covers a large azimuthal extent on the white dwarf, as would likely be produced from a boundary layer. On the other hand the pulsations in V407 Vul and J0806 suggest localized emission on the white dwarf surface.

The detection with *Chandra* of hard (> 2 keV) emission from ES Cet as well as the suggestive evidence for line features indicates that a hard, optically thin, line dominated spectral component similar to that seen from GP Com can still be produced even at very high mass accretion rates. Clearly deeper high resolution spectroscopy of ES Cet as well as GP Com, with, for example, XMM/Newton, has the potential to probe in detail the composition and physical properties of the boundary layers in these systems. Moreover, comparisons between a low $\dot{m}$ system such as GP Com, and a high $\dot{m}$ system like ES Cet can provide important information on the mass accretion rate dependence of the boundary layer spectrum and structure.

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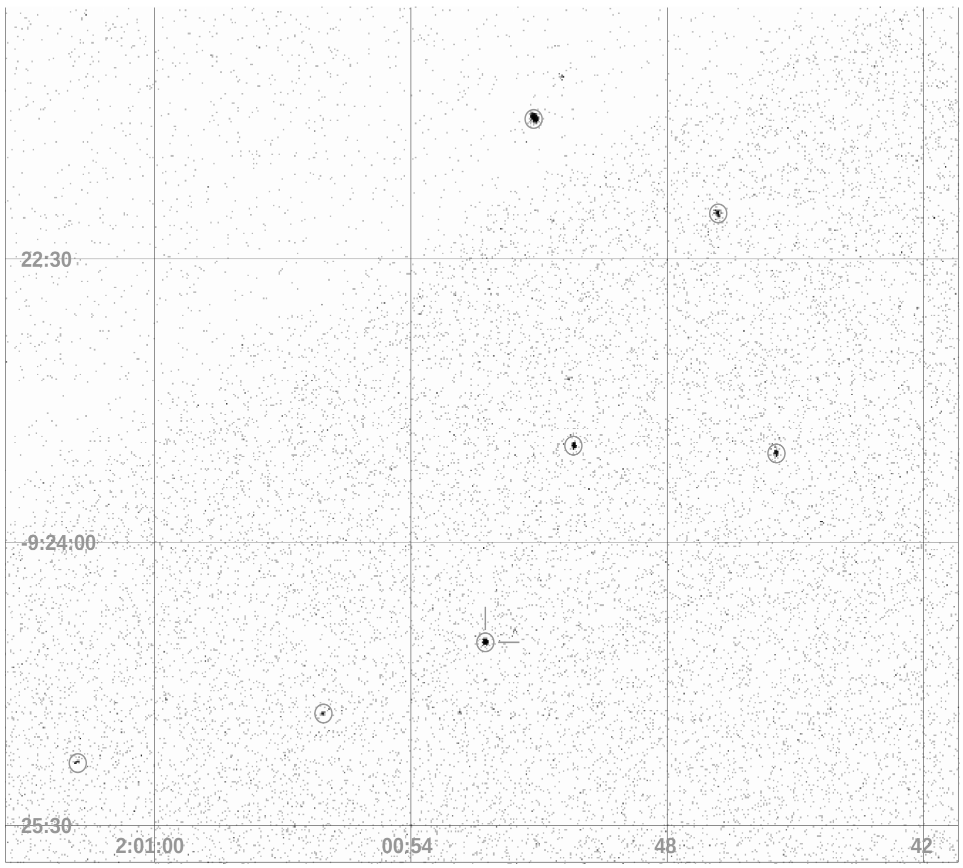

Figure 1: Chandra/ACIS-S 0.2 - 10 keV image of the region around ES Cet. Seven previously unknown sources are identified with 3” radius circles. The position of ES Cet is additionally marked by the pair of orthogonal lines.

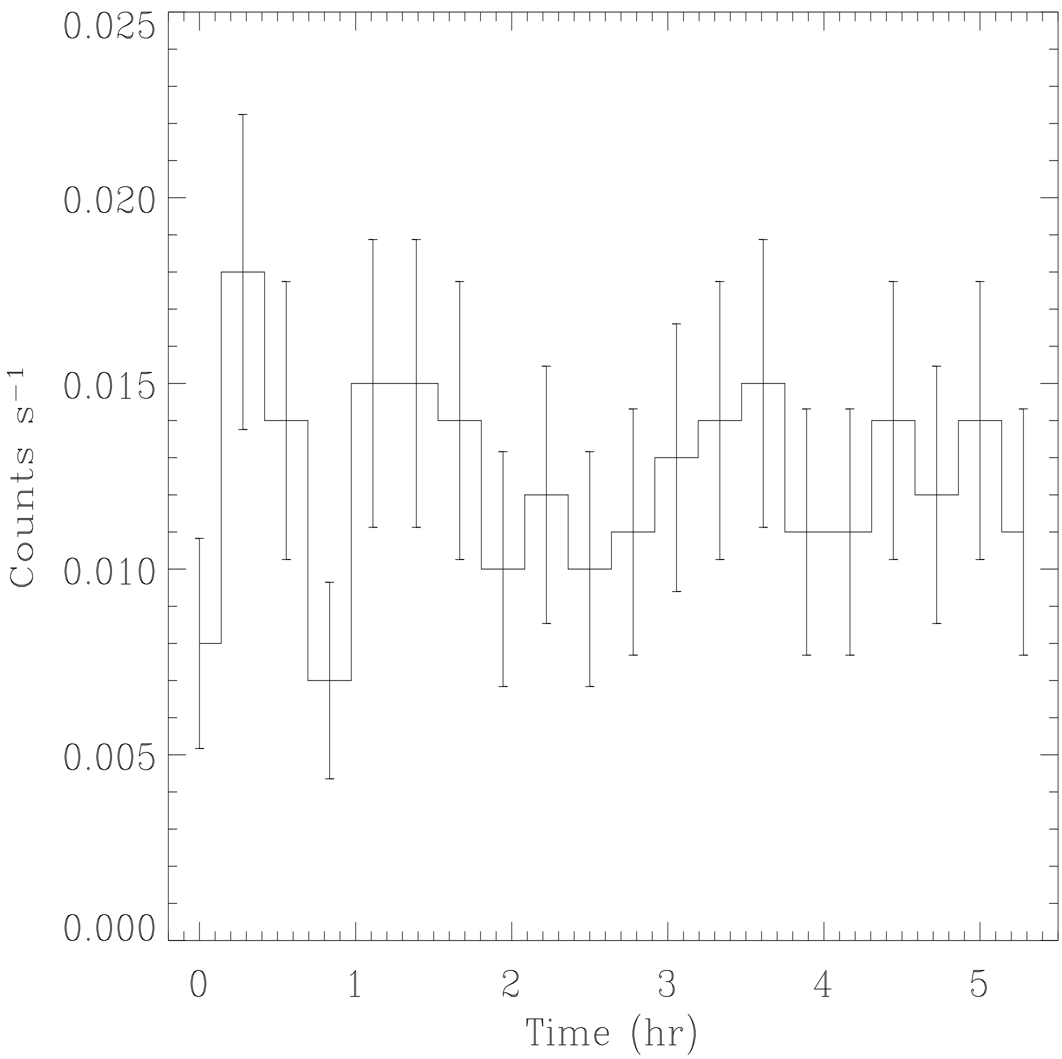

Figure 2: Lightcurve of ES Cet in the full *Chandra* band. The time bins are 1000 s. There is no evidence for variability.

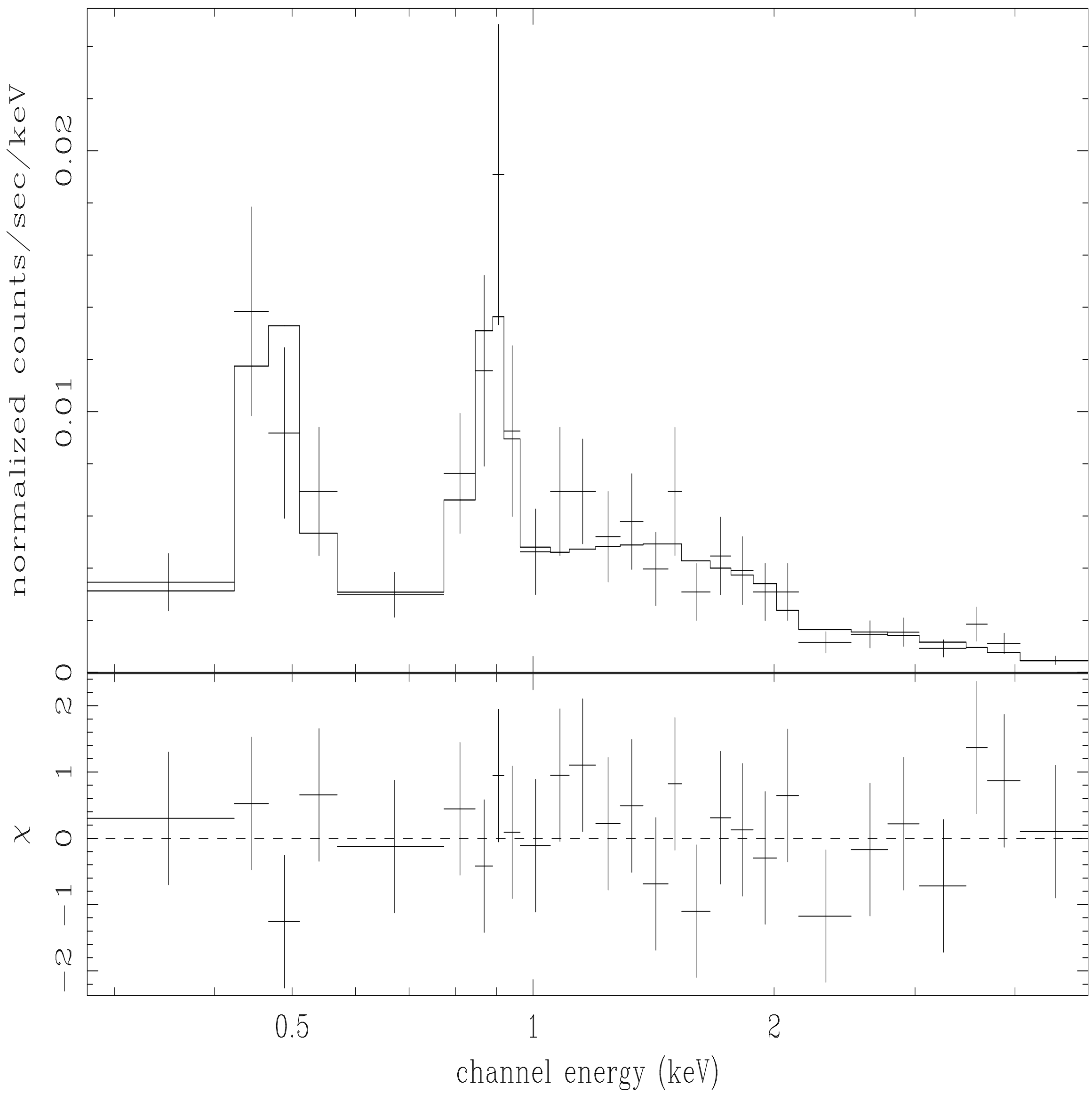

Figure 3: ACIS-S data and best fitting spectral model. The model includes black body emission with $kT = 0.8$ keV, as well as narrow gaussian emission lines at 470 and 890 eV. See Table 2 for details of the spectral modeling.

Table 1: X-ray Sources in the Vicinity of ES Cet

Source	RA (J2000)	DEC (J2000)	Count Rate (s^{-1})[1]
CXO 020052.2-092431.6 (ES Cet)	02:00:52.23	-09:24:31.68	0.0101
CXO 020056.0-092454.4	02:00:56.05	-09:24:54.40	0.0011
CXO 020050.1-092329.2	02:00:50.18	-09:23:29.26	0.0045
CXO 020101.8-092509.5	02:01:01.82	-09:25:09.52	0.0012
CXO 020051.1-092145.3	02:00:51.10	-09:21:45.32	0.0012
CXO 020046.8-092215.4	02:00:46.81	-09:22:15.49	0.0007
CXO 020045.4-092331.6	02:00:45.43	-09:23:31.60	0.0027

[1] Background subtracted count rate.

Table 2: X-ray Spectral Fits for ES Cet

Model	kT/α^1	Norm^2	Flux^3	E_1^4	$\text{Flux}_{E_1}^5$	E_2^4	$\text{Flux}_{E_2}^5$	χ_r^2
powerlaw	0.95 ± 0.1	1.1×10^{-5}	6.7	-	-	-	-	1.4
blackbody	0.68 ± 0.05	0.029	6.1	-	-	-	-	1.84
powerlaw + lines	0.88 ± 0.14	8.1×10^{-6}	7.1	471 ± 29	3.1	891 ± 29	1.9	0.95
blackbody + lines	0.79 ± 0.08	0.017	6.9	470 ± 19	4.7	890 ± 23	2.3	0.60

[1] Temperature in keV (for blackbody), or power law index.

[2] Continuum normalization parameter.

[3] Model flux in units of 10^{-14} ergs cm^{-2} s^{-1}.

[4] Line centroid in eV.

[5] Line flux in units of 10^{-6} photons cm^{-2} s^{-1}.